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ELECTROMAGNETIC INTERACTIONS WITH ADVANCED COMPOSITE MATERIALS.(U)
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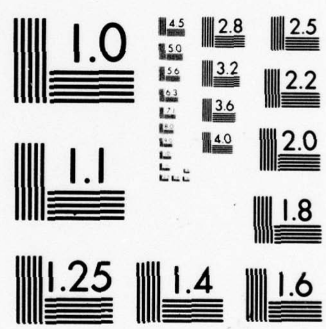

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ELECTROMAGNETIC INTERACTIONS WITH ADVANCED COMPOSITE MATERIALS

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ABSTRACT

Research objectives and accomplishments under AFOSR Grant No. 76-2980 are described. These include studies of plane electromagnetic wave interactions with planar sheets, circular cylindrical shells, and spherical shells of advanced composite materials; and a study of the effects of transient current injection into a planar sheet of advanced composite material. The effects of anisotropy of composite laminates on their electromagnetic characterization and interactions are also discussed. The frequency range over which the electromagnetic characterizations and interaction analyses are valid is that characteristic of the nuclear electromagnetic pulse.

I. RESEARCH OBJECTIVES

The general objective of this research program was to develop an improved understanding of the interaction of electromagnetic radiation with advanced composite materials, over the frequency range characteristic of the nuclear electromagnetic pulse (EMP) or lightning ($f \leq 10^8$ Hz). The general objective was to be attained through the consideration of certain specific problems which are described below. The solutions of these problems constituted the specific research objectives of this program.

<u>Specific problems to be addressed</u>

1. Transmission of plane electromagnetic waves through a planar slab of conductive (e.g., graphite-epoxy) composite of infinite transverse extent; and similarly for a poorly conducting (e.g., boron-epoxy) composite with a bonded-junction wire mesh embedded in one surface.

2. Penetration of plane electromagnetic waves into an infinitely long circular cylindrical shell of conductive composite; and similarly for a poorly conducting composite with a bonded-junction wire mesh embedded in one surface.

3. Study of the effects of anisotropy on the electromagnetic characterization of advanced composites and on their interactions with electromagnetic fields.

4. Determination of the surface current density and the electromagnetic field associated with transient current injection into a planar slab of advanced composite of infinite transverse extent.

5. Analysis, via the Singularity Expansion Method, of transient plane electromagnetic wave interaction with a hollow spherical shell of advanced composite, including both conductive and screened nonconductive composites as special cases.

The solutions of these specific problems entailed the definition and consideration of related problems which led to the concept of the "boundary connection supermatrix" and to the development of an equivalent sheet-

impedance operator describing a bonded-junction wire mesh on a dielectric substrate. The results obtained from consideration of these problems and those listed above are summarized in the next section.

II. SUMMARY OF RESEARCH ACCOMPLISHMENTS

The problems of plane electromagnetic wave transmission through a planar slab of advanced composite material and of electromagnetic penetration into an infinitely long cylindrical shell are discussed in detail in [1]. The development of the boundary connection supermatrix and of the equivalent sheet impedance operator for a bonded junction wire mesh on a dielectric substrate is also described there. The composite laminates were modeled by <u>isotropic</u> conductive or dielectric materials for the purposes of that study, and both the frequency and time domains were considered. The frequency range and the time-domain waveforms were characteristic of the nuclear electromagnetic pulse. Specific accomplishments reported in [1] include:

A. Development of boundary connection operators or supermatrices to describe electromagnetic boundary condition relations across single dielectric or conductive layers, sheet immittances, and general combinations of layers and/or sheet immittances.

These operators take the form of matrices of dyadics (supermatrices) which connect, or relate, the tangential components of the electric and magnetic fields on one side of a (possibly multilayered) wall to those on the other. Their utility lies in the fact that a complicated wall structure can be described in the form of a matrix whose elements can be found from relatively simple analyses of planar structures; the matrix boundary connection can then be used in problems where the wall is non-planar or may even have variable spatial properties. The number of distinct regions which must be considered in a given boundary-value problem can therefore be reduced, thus simplifying the analysis.

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[1] K.F. Casey, "Electromagnetic shielding by advanced composite materials", <u>Interaction Notes</u>, Note 341, January 1978.

B. Analysis of plane-wave interactions with a planar graphite composite shield, in frequency and time domains.

This analysis, although straightforward, was useful in demonstrating the use of the boundary connection supermatrix in boundary-value problems and in quantifying the shielding effectiveness of graphite composities. It was found that a panel of such a material affords approximately 80 dB of shielding (frequency domain) and that the peak value of a double-exponential EMP signal is attenuated by a similar amount in passing through such a panel.

C. Analysis of plane-wave interactions with an infinitely long cylindrical shell of graphite composite, in frequency and time domains.

Since an enclosed region provides negligible electromagnetic shielding at sufficiently low frequencies, it is important to determine the critical frequency below which the shielding is seriously degraded. For a graphite composite cylinder this critical frequency is approximately $(\pi\mu_o\rho_o\sigma_g d)^{-1}$, in which μ_o denotes the permeability of free space, ρ_o the cylinder radius, σ_g the conductivity of the composite, and d the thickness of the wall. For a cylinder of radius 1 m, this frequency is of the order of 10 kHz. The peak value of the time-domain magnetic field inside a cylindrical graphite composite shell of radius 1 m and thickness 1.5 mm was found to be reduced by approximately 60 dB, when a double-exponential EMP waveform was normally incident on the shell. The internal waveform is greatly broadened in comparison to the incident waveform as a consequence of the low-pass characteristics of the graphite composite itself and of the cylindrical geometry.

D. Analysis of plane-wave interactions with a planar nonconductive composite panel and an embedded wire mesh, in frequency and time domains.

The bonded-junction wire mesh which can be used to improve the shielding effectiveness of a poorly conductive or nonconductive composite greatly complicates the analysis of problems involving electromagnetic

interactions with such materials. The approach which was taken in this analysis was to characterize the mesh by an equivalent sheet impedance operator; once this was accomplished, the plane-wave interaction analysis was straightforward. The equivalent sheet impedance operator for a mesh in free space has long been known [2]; the principal accomplishment of this part of the effort was to determine how this operator is modified by the presence of a dielectric substrate. It was found that a "screened" nonconductive composite can be very effective in reducing the peak value of an electromagnetic wave transmitted through it; but because of the high-pass character of a bonded-junction mesh, the waveform was significantly "sharpened" in transit. Generally, it was found that the mesh size (and thus its equivalent inductive reactance) tended to influence the early-time part of the transmitted waveform, with smaller meshes tending to reduce the amplitude of this early-time part; and that the wire conductivity primarily influenced the late-time part of the transmitted waveform. As would be expected, the best shielding is provided by a fine mesh of highly conductive wires.

E. Analysis of plane-wave interactions with an infinitely long cylindrical shell of nonconductive composite and an embedded wire mesh, in frequency and time domains.

The equivalent sheet impedance operator derived for the planar geometry was used together with the boundary connection supermatrix in this analysis. It was found that the high-pass character of a bonded-junction mesh and the low-pass character of the cylindrical geometry tended to cancel each other, so that the time-domain waveform of the magnetic field inside the cylinder tended to resemble that of the incident field. In this geometry the wire conductivity tended to dominate the shielding behavior of the composite, because the inductive effect of the mesh was compensated to an extent by the geometry itself. It was concluded that for cylindrical geometries

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[2] M.I. Kontorovich, "Averaged boundary conditions at the surface of a grating with square mesh", Radio Engineering and Electronic Physics, vol. 8, pp. 1446 - 1454, 1963.

(or, indeed, for any enclosed-region geometry) a fine mesh screen on a nonconductive composite substrate was perhaps a better electromagnetic shield than a graphite composite.

The effects of anisotropy of advanced composite laminates are discussed in [3]. A laminate with a "quasi-isotropic" layup (e.g., 0° - 45° - 90°) in which there is no preferred fiber orientation is found to be described by a uniaxially anisotropic permittivity or conductivity. The conductivity (or permittivity) in directions parallel to the laminate's surface generally differs from that in the normal direction. Only the "tangential" conductivity is of major importance in electromagnetic interactions with conductive composites, so that analyses of such interactions based on isotropic models are very accurate if the isotropic-model conductivity is taken to be equal to the tangential conductivity in the anisotropic model. The effective relative permittivity of an anisotropic nonconductive composite laminate is found to be the geometric mean of the transverse and normal permittivities, insofar as its effect on the equivalent sheet impedance operator of an embedded bonded-junction wire mesh is concerned. Therefore, analyses of electromagnetic interactions with "screened" nonconductive composite laminates based on isotropic models are very accurate if the isotropic-model permittivity is taken to be equal to the geometric mean of the transverse and normal permittivities of the anisotropic model. Anisotropy, per se, does not appear to be a complicating factor in electromagnetic analyses of advanced composites, at least over the EMP frequency spectrum.

The problem of assessing the effects of lightning-stroke interaction with an advanced composite laminate was addressed via an idealized canonical problem, that of determining the surface current density and the electromagnetic field associated with transient current injection into a planar sheet of composite material. The analysis and the results are described in [4]. It was found that over the frequency range characteristic of the

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[3] K.F. Casey, "EMP penetration through advanced composite skin panels", Interaction Notes, Note 315, December 1976.

[4] K.F. Casey, "Transient current injection into a resistive sheet", Interaction Notes (to appear).

lightning return stroke ($f \leq 10^5$ Hz), both conductive and screened nonconductive composite laminates can be modeled as resistive sheets. Using this model, it has been shown that

1. the surface current density in the sheet is nearly identical to that which would exist if the sheet were perfectly conducting, and
2. the magnetic field beneath the sheet is very small in comparison to that above the sheet; furthermore,
3. the time dependence of the magnetic field beneath the sheet is proportional to the time derivative of the injected current waveform.

These results follow if realistic values of the equivalent sheet resistance of the composite panel are used in the model. The first of these results can greatly simplify the analysis of problems related to thermal effects of current injection, since the current density can be accurately calculated on the assumption that the surface is perfectly conducting. The results of this calculation can then be used in conjunction with the thermal and electrical properties of the composite panel to determine, for example, the temperature rise resulting from the injected current.

Electromagnetic wave interactions with a hollow spherical shell of advanced composite material are described in [5]. Both conductive and screened nonconductive composites are considered, and the SEM (Singularity Expansion Method) is employed in the analysis. The objective of the analysis was to determine the location of, and the residues at, the s-plane poles corresponding to the interior and exterior resonances, as functions of the parameters descriptive of the composite shell. The SEM expansions of the internal and scattered field response functions and the electric and magnetic surface current and charge density response functions, and the natural modes and coupling coefficients were found. Numerical results were

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[5] K.F. Casey, "SEM analysis of transient electromagnetic plane wave interaction with a hollow spherical shell of advanced composite material", Interaction Notes (to appear).

obtained to illustrate the behavior of certain of these quantities as the composite shell parameters were varied. It was found that in addition to the anticipated internal and external resonances, there exist additional characteristic resonances arising from the finite specific resistance of the shell material. These resonances, together with the s-plane poles of the incident waveform (in the transform domain), are of primary importance in determining the late-time or quasi-static fields inside the sphere. An important difference between the conductive and screened nonconductive composite shells is that while the conductive shell completely excludes the quasi-static electric field from its interior, the screened nonconductive composite can be penetrated by such a field.

III. TECHNICAL PUBLICATIONS (Author: K.F. Casey)

A. Air Force Weapons Laboratory Interaction Notes

1. "EMP penetration through advanced composite skin panels", IN 315, December 1976.

2. "Electromagnetic shielding by advanced composite materials", IN 341, January 1978.

3. "Transient current injection into a resistive sheet" (to appear).

4. "SEM analysis of transient electromagnetic plane wave interaction with a hollow spherical shell of advanced composite material" (to appear).

B. Journal articles in preparation

1. "Electromagnetic theory of dielectric-backed bonded-junction mesh screens", to be submitted to IEEE Transactions on Electromagnetic Compatibility.

2. "The boundary-connection supermatrix and electromagnetic shielding", to be submitted to IEEE Transactions on Electromagnetic Compatibility.

IV. PROFESSIONAL PERSONNEL

A. Principal Investigator

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B. Undergraduate Research Assistants

Glenn Engel

Clay Jones

John Waterman

Harold Roesler

David Soldan

V. INTERACTIONS (COUPLING ACTIVITIES)

A. Papers presented at technical meetings (author: K.F. Casey)

1. "Equivalent sheet impedance of a bonded-mesh screen on an anisotropic half-space", USNC/URSI Meeting, Stanford, California, June 1977.

2. "SEM analysis of a hollow spherical shell of 'screened' composite material", National Radio Science Meeting, Boulder, Colorado, January 1978.

3. "EMP shielding and advanced composite materials", Nuclear EMP Meeting, Albuquerque, New Mexico, June 1978.

4. "Boundary connection supermatrices and electromagnetic shielding calculations", Nuclear EMP Meeting, Albuquerque, New Mexico, June 1978 (coauthor: C.E. Baum).

5. "Advanced composite materials and electromagnetic shielding", International Symposium on Electromagnetic Compatibility, Atlanta, Georgia, June 1978.

6. "Boundary connection supermatrices", National Radio Science Meeting, Boulder, Colorado, November 1978.

B. Other oral presentations

1. "Transient current injection into a conducting sheet", Lightning Analysis for Aircraft Design Workshop, Naval Ocean Systems Center, San Diego, California, July 1978.

2. A presentation on advanced composite materials and electromagnetic shielding at IEEE Joint Chapter (AP-S, MTT, EMC) Meeting, Albuquerque, New Mexico, August 1977.

3. Presentations on the above topic to Electrical Engineering Department Seminars at Kansas State University, the University of California at Los Angeles, and the University of California, Berkeley.

c. Consultative and advisory activities

No such activities were carried out on a formal basis. I have been involved in many informal discussions of advanced composite materials with personnel of the Air Force Weapons Laboratory, Air Force Flight Dynamics Laboratory, other DoD organizations and contractors, and other universities.

VI. NEW DISCOVERIES, INVENTIONS OR PATENT DISCLOSURES AND SPECIFIC APPLICATIONS STEMMING FROM THE RESEARCH EFFORT

New discoveries were of a scientific nature and are described in Section II, Summary of Research Accomplishments. No inventions or patent disclosures resulted from this research effort.

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